The Gulf Stream and Its Problems

Florida-The Gulf Stream and its

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THE GULF STREAM AND ITS PROBLEMS [1]

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285 Maury's The Physical Geography of the Sea, which appeared in 1855, is frequently referred to as the first textbook of modern oceanography. In that work the author devotes the first chapter to the Gulf Stream, introducing it thus:

> There is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows. Its banks and its bottom are of cold water, while its current is of warm. The Gulf of Mexico is its fountain, and its mouth is in the Arctic Seas. It is the Gulf Stream. There is in the world no other such majestic flow of waters. Its current is more rapid than the Mississippi or the Amazon. [2]

Even in matters scientific, customs change. It is altogether unlikely that an oceanographer nowadays would speak of the Gulf Stream as rhetorically as did Maury. The magnitude of this current, however, is such that even later students make use of superlatives in describing it. The most comprehensive investigation of the Gulf Stream was carried out between the years 1885 and 1889 by Lieut. (later Rear Admiral) J. E. Pillsbury, United States Navy, while attached to the Coast and Geodetic Survey. And when he came to write up the results of his observations and studies he described it as "the grandest and most mighty * * * terrestrial phenomenon." [3]

Of all the currents that make up the systems of oceanic cir-
culation, the Gulf Stream has received the greatest amount of
study and is the best known. Its discovery, or more accurately
the first notice on record, came shortly after the discovery of the
new world. Early in March of 1513, Ponce de Leon set sail from
Porto Rico with three ships on a voyage of exploration. Setting
a northwesterly course the expedition discovered Florida, a landing
being made on the eastern coast somewhere in the general vicinity
of Cape Canaveral. Sailing southerly then they encountered on
April 22, as related in a chronicle of the expedition, "a current
p.286 such that, although they had a great wind, they could not proceed
forward, but backward, and it seemed that they were proceeding
well; and in the end it was known that it was in such wise the cur-
rent which was more powerful than the wind."[4] Thus was the Gulf
Stream first noted.

Apparently the Spaniards soon learned that this northerly flowing current was not merely a local current but one of wide extent; for six years later, when Antonio de Alaminos set out for Spain from Vera Cruz, he sailed northward with the Gulf Stream for a number of days before turning east toward Europe. This same Alaminos was pilot of Ponce de Leon's expedition of 1513 when the Gulf Stream was first noted. It is therefore quite proper to credit the discovery of the Gulf Stream to Alaminos.

Earliest Gulf Stream Chart

For two and a half centuries following its discovery the growth of knowledge regarding the Gulf Stream was slow. The story is told in detail by Kohl[5] and more briefly by Pillsbury. During this period, to be sure, the mariner, and more especially the whaler, became acquainted with the Gulf Stream throughout the greater part of its course. Much of this information, however, was kept as a professional secret, and it was not until after the middle of the eighteenth century that the course of the current was depicted on a chart. The story of how this came about is not without interest, especially as it illustrates nicely the effect of the Gulf Stream on navigation.

About 1770, complaint was made to the London officials that the English packets which came to New York took about two weeks longer in crossing then did the Rhode Island merchant ships which put in at Naragansett Bay ports. Benjamin Franklin, being in London at the time, was consulted about the matter. To quote his own words:

> It appearing strange to me that there should be such a difference between two places, scare a day's run asunder * * * I could not but think the fact misunderstood or misrepresented. There happened then to be in London a Nantucket sea captain of my acquaintance, to whom I communicated the affair. He told me he believed the fact might be true; but the difference was owing to this, that the Rhode Island captains were acquainted with the

Gulf Stream, which those of the English packets were not * * * When the winds are but light, he added, they are carried back by the current more than they are forwarded by the wind * * * I then observed that it was a pity no notice was taken of this current upon the charts, and requested him to mark it out for me, which he readily complied with, adding directions for avoiding it in sailing from Europe to North America.[6]

p. 287 [Franklin goes on to relate that he had the information engraved "on the old chart of the Atlantic, at Mount and Page's, Tower-hill; and copies were sent down to Falmouth for the captains of the packets who slighted it however; but it is since printed in France, of which edition I hereto annex a copy." (Fig. 1)

As evidenced by Franklin's letter in the Transactions of the American Philosophical Society, the Gulf Stream towards the end of the eighteenth century became a subject of scientific investigation and discussion. Franklin himself made observations on the temperature of the sea water during a number of voyages and noted with regard to the Gulf Stream "that it is always warmer than the sea on each side of it." By the middle of the nineteenth century, when systematic observations were begun, a fund of information had been gathered from navigators' logs and from the observations of scientifically minded travelers.

Systematic Observations

Systematic observations in the Gulf Stream were begun in 1845 by the Coast Survey under the superintendency of Alexander

Dallas Bache, a great grandson of Franklin. At different times up to the year 1889 specially equipped vessels were detailed for the work, the results being published as appendixes to the annual reports of the Superintendent of the Coast and Geodetic Survey,
268 the last one being that by Pillsbury cited in footnote 3. In passing, it is to be noted that this systematic work was confined almost wholly to the Gulf Stream along the coast of the United States.

The published material on the Gulf Stream is extensive. Here it will be sufficient to direct attention only to the more authoritative recent work. Krummel, in what is still the standard treatise on oceanography,[7] gives a brief but critical summary of the hydrographic features of the Gulf Stream as developed to the end of the first decade of the present century, and Schott[8] brings the discussion up to the present time. And, while dealing with but a restricted part of the Gulf Stream, Wust's study[9] should be mentioned here because it represents a successful attempt to correlate and elucidate the phenomena involved in the Gulf Stream by means of mathematical, or more accurately perhaps, dynamical methods.

It is customary to trace the last remnant of the Gulf Stream into the Arctic waters north of Norway. From its place of origin in the Gulf of Mexico, therefore, this current traverses a route of more than 6,000 miles. But it is not as a "river in the ocean"

that it manifests itself throughout its course. The phenomena presented are much more involved, and the stream is to be regarded rather as a complex system of currents than as a single current. We may arrive at an understanding of the nature of the forces and factors involved by a brief consideration of its characteristics in the region in which it has been most carefully studied.

The Current in the Straits of Florida

It is in its first reach, through the Straits of Florida, that the characteristics of the Gulf Stream are most marked. Here its waters have the highest temperature and salinity and the swiftest flow. And because it is here confined within a restricted channel it lends itself more readily to investigation. Observations have here been made across a number of sections; and with this stretch, too, Wust's study mentioned above is concerned.

Figure 2, which is adapted from Coast and Geodetic Survey Chart 1007, visualizes the hydrographic features of the Gulf Stream for the first 400 miles of its course. The region where the Gulf of Mexico narrows to form the channel between Florida Keys and Cuba may be regarded as the head of the Gulf Stream. Here the width of its channel is 95 nautical miles. Eastward the channel becomes narrower, reaching its least width in the so-called narrows, abreast of Cape Florida, where it is but half its original width. From here it widens somewhat until it meets the open sea north of Little Bahama Bank.

p. 289 While the chart shows that in its first reach the Gulf Stream flows between banks like a river, it is to be noted that this channel is in two respects markedly different from that of a river. In a river, as a rule, the channel increases in width from head to mouth. But in the Gulf Stream, as we have just seen, the width of the channel decreases seawards. Futhermore, a river deepens as it goes seaward; an examination of the chart, however, shows that

. 290 the channel of the Gulf Stream becomes shallower as it goes seaward. At its head, as shown in Figure 2, the stream shows depths of a thousand fathoms or more; but the depths gradually decrease, and when the channel approaches the sea the greatest depth is but little more than 400 fathoms.

Nautical charts are issued primarily for the mariner, to whom the shoal areas are critical. Hence in hydrographic surveys, as a rule, shoal areas are much more closely developed than areas of deep water, So that it may be assumed that the relief of the bottom of the Straits of Florida is indicated only in its larger features on the chart. It is quite likely that a detailed hydrographic survey of the straits would bring out interesting local features that now are masked.

Throughout the whole stretch of 400 miles shown in Figure 2, the Gulf Stream flows with considerable velocity. It is clear, however, that the whole mass of water is not moving with a uniform velocity. Confining our attention for the present to the velocity

of the current at the surface we find at its head, say abreast of Habana, the velocity in the axis of the stream (shown by arrows in fig. 2) to be about $2\frac{1}{2}$ nautical miles per hour, or $2\frac{1}{2}$ knots on the average. Seaward, the velocity increases gradually as the cross-sectional area of the stream decreases until abreast of Cape Florida the velocity becomes about $3\frac{1}{2}$ knots. As we shall see later, the current is subject to variations; and it is therefore to be emphasized that the velocities given above are approximate average or normal velocities.

With regard to the current within the depths of the Gulf Stream the observational data are in general fragmentary. Pillsbury during his investigation carried out several series of current observations in the Straits of Florida, but these were generally confined to depths less than 1,000 feet. From these observations and from general considerations it is known that the swiftest thread of the current lies in the axis of the stream, just below the surface, and from here the velocity decreases with increasing depth. In the axis of the Gulf Stream, off Habana, Pillsbury found the current setting easterly with a velocity of a knot at a depth of 130 fathoms.

Within the narrows of the strait, abreast of Cape Florida, the velocity distribution may be considered relatively well known. Figure 3, adapted from Wust, shows the velocity distribution

291 across the section just south of Cape Florida. In constructing the velocity curves Wust made use of Pillsbury's observations; and for the deeper parts, for which no observations are at hand, he derived the necessary data from a consideration of the temperature and salinity observations, which here extended from the surface to the bottom.

Within the Straits of Florida the Gulf Stream is generally pictured as a swiftly moving stream with but little variation in velocity from surface to bottom. Figure 3 shows, however, that only within a layer of about 200 fathoms (1,200 feet) does the velocity exceed 1 knot. Moreover, near the bottom, Pillsbury found the current setting southerly, that is, in a direction opposite to that of the main stream. This was taken to indicate a southerly flowing current, deriving perhaps from the Labrador Current. It appears, however, that it is more reasonably to be ascribed to eddies brought about by the upward-sloping bottom within the Straits of Florida.

With the details of the velocity distribution known, it becomes possible to compute the volume of water discharged by the Gulf Stream through the Straits of Florida. A rough estimate is easily made from Figure 3. In round numbers the channel eastward of Cape Florida has a width of 42 (geographical) miles and an average depth of 2,000 feet, or approximately one-third of a mile. This gives the area of the cross section here as 14

square miles. In round numbers, also, the velocity of the current through this section may be taken as 1 knot. Each hour, therefore, the Gulf Stream carries 14 cubic miles of water past this section into the sea. Since a geographical mile has a length of 6,080 feet and a cubic foot of sea water weighs approximately 64 pounds, we find that each hour the Gulf Stream carries 100 billion tons of water past Cape Florida into the sea.

The above calculation is clearly no more than a rough estimate; but it demonstrates that the hourly volume of the Gulf Stream is to be reckoned in scores of billions of tons. On the basis of his observations Pillsbury calculated the hourly volume of the Gulf Stream through the Straits of Florida as 90 billion tons. More recently Wust, on the basis of data furnished by the observations and amplified by dynamical considerations, derived for this volume 89.96 cubic kilometers, or 14.1 cubic miles, which equals 101½ billion tons. In round numbers we may therefore take the average hourly volume of the Gulf Stream through the Straits of Florida to be 100 billion tons.

We may perhaps appreciate better the enormous volume of water that the Gulf Stream pours into the sea by comparing it with the volume discharged by the Mississippi River, which drains more than 40 per cent of the area of continental United States. On the average the Mississippi discharges about 644,000

292 cubic feet of water into the Gulf of Mexico each second. At extreme flood stage this volume becomes multiplied about threefold, mounting to about 1,800,000 cubic feet per second.[10] On converting these figures into cubic (geographical) miles per hour they become, respectively, 0.01 and 0.03 cubic mile. The 14 cubic miles which the Gulf Stream hourly pours into the sea is thus more than 1,000 times the average discharge and very nearly 500 times the extreme flood discharge of the Mississippi.

The Water within the Straits of Florida

With regard to the water poured so prodigally by the Gulf Stream into the sea through the Straits of Florida, the generally accepted notion is that it is of an unusually high temperature from top to bottom. Figure 4 shows the temperature of the water, in degrees Fahrenheit, across the section in the straits from Cape Florida eastward. This is adapted from Wüst, who made use of observations taken in May 1878, and in March 1914. Since, in general, the sea in the Northern Hemisphere is coldest in February and warmest in August, it may be taken that the temperatures shown in Figure 3 are approximately average temperatures.

Obviously the Gulf Stream in the straits is not a homogeneous body of warm water. At the surface, in the center of the channel, the temperature is about 80°, and at the bottom it is 45° or even less. The fall in temperature is fairly rapid, a temperature of 50° being attained at about 200 fathoms, so that only a relatively shallow layer of the water is warm.

Figure 3 brings to light the fact that for any given depth the water on the eastern side of the channel is considerably warmer than that on the western. Thus at a depth of 100 fathoms the water on the Florida side of the straits has a temperature of about 50°, while on the Bahama side the temperature is about 70°. Futhermore, while the change in temperature with depth is approximately uniform on the Bahama side, it is decidedly not uniform on the Florida side, where a rapid change of 20° in temperature takes place between the depths of 50 and 100 fathoms. As regards temperature therefore, the water of the Gulf Stream is decidedly not homogeneous.

The prevailing conception of the Gulf Stream as an unusually warm body of water can be shown as erroneous from
293 another point of view, /namely, by comparison with other bodies of water in the same latitude, for example, with the Sargasso Sea. The surface waters of the Gulf Stream in the Straits of Florida have about the same temperatures as the surface waters of the Sargasso Sea. But within the depths the Sargasso Sea is much warmer. At a depth of 200 fathoms the temperature of the latter is between 60° and 65°,[11] while in the Gulf Stream at that depth the temperature, as shown by Figure 4, averages about 55°.

With regard to other characteristics there is a like tendency to overrate the waters of the Gulf Stream. Highly saline these waters are, but not exceptionally so. On the customary salinity scale, in which each unit represents one part of salt in a thousand parts of water, the surface waters within the straits have a salinity of about 36. Below the surface the salinity increases gradually until a maximum of 36½ is reached at a depth of about 100 fathoms, after which the salinity decreases to about 35 at 300 fathoms, which salinity is then maintained to the bottom. In round numbers we may take the salinity of the waters within the straits as a whole to be 36. Compared to the average salinity of 34 3/4, which is accepted as the figure for the sea as a whole, the water within the straits is highly saline; but toward its eastern end the Sargasso Sea is more saline, having a salinity of 37½ on the surface and of about 36 at a depth of 300 fathoms. In depth of color and transparency, the waters in the Sargasso Sea likewise exceed those of the Gulf Stream.

In general, however, the Gulf Stream as it issues into the sea through the Straits of Florida may be characterized as a swift, highly saline current of blue water whose upper stratum is composed of warm water.

Union with the Antilles Current

On issuing into the sea north of Little Bahama Bank the Gulf Stream loses the relatively great velocity which characterized it

within the straits. From $3\frac{1}{2}$ knots along the axis within the narrows of the straits, there is a gradual decrease to a velocity of about 2 knots off St. Augustine, Fla., in latitude 30° N. Here the Gulf Stream is joined by the Antilles Current, which flows northwesterly along the open ocean side of the West Indies before uniting with the Gulf Stream.

North of the thirtieth parallel of latitude, therefore, the Gulf Stream is a current to which two branches have contributed. It is no longer merely a continuation of the current that flows through the Straits of Florida. The latter current, for distinction, is frequently referred to as the Florida Current. As to the relative importance of the two branches of the Gulf Stream widely varying
294 opinions have been entertained. Formerly it was thought that the Antilles Current furnished both the greater quantity of water as well as the greater quantity of heat transported by the Gulf Stream. Krummel, for example, credits the Antilles Current with contributing about 2 3/4 times as much water and heat as the Florida Current. Wust's study of the question, however, makes it appear that the roles of the two currents must be reversed; for he finds on the basis of later data, that the Florida Current contributes about twice as much water and heat as the Antilles Current.

The Antilles Current, like the Florida Current, carries warm, highly saline water of clear indigo blue. The union of the two currents gives rise to a broad current possessing about the same

characteristics as the Gulf Stream within the straits except that the velocity is much reduced. The combined current, under the influence of the deflecting force of the earth's rotation and the easterly trending coast line, turns more and more easterly, so that off the coast of Georgia the Gulf Stream bears northeast, maintaining this general direction past Cape Hatteras.

The Axis of the Stream

From within the straits the axis of the Gulf Stream runs approximately parallel with the 100-fathom curve as far as Cape Hatteras, a distance of about 800 geographical miles. Since this stretch of coast line sweeps northward in a sharper curve than does the 100-fathom line, the axis lies at varying distances from the shore. Within the straits it is about 10 miles offshore; in the bight off the coast of Georgia this distance is about 100 miles; and at Cape Hatteras it is about 35 miles. In Figure 5 the axis is shown as compiled from Coast and Geodetic Survey Charts, 1007 and 1001 and Hydrographic Office Chart 1411. On these charts the axis bears the following legends: "approximate axis of maximum strength" (Chart 1001); "approximate location of axis of Gulf Stream" (Chart 1007); mean position of axis of Gulf Stream" (Chart 1411).

Even with a qualifying phrase directing attention to the fact that its location is only approximate, the axis of the Gulf Stream as it appears on a chart tends to convey a sense of definiteness and precision wholly at variance with the observed facts. The

channel of the Gulf Stream is so wide and is characterized by so many irregularities that the simple flow postulated can be but the roughest approximation.

Strictly, we should distinguish between the temperature axis and the velocity axis of the Gulf Stream. The earlier systematic observations on the Gulf Stream dealt with the temperature of the water rather than with its motion. Hence the axis was taken to be the line along which the highest temperatures obtained. Later, the axis was taken to mark the line of greatest velocity. Ordinarily
96 it is assumed that the two axes coincide; but this is by no means certain and only systematic observations over a considerable period can solve this problem.

Lateral Boundaries

Within the straits the lateral boundaries of the Gulf Stream can be fixed with considerable precision. But when the stream issues into the sea, how are these boundaries to be determined? On the western side, to be sure, it is not difficult to define limits, since the waters of the stream differ in color, temperature, salinity, and flow from the inshore coastal waters. But on the east the Antilles Current comes to reinforce the Gulf Stream, so that its waters here merge gradually with the waters of the open Atlantic. In terms of color, temperature, and salinity it would be difficult to define the eastern limits of the Gulf Stream. With regard to direction of flow, however, we may fix the limits to include all

the water flowing parallel to the axis. These limits vary with the seasons and with changing conditions of wind and weather. Furthermore, our knowledge of currents in the open sea is not yet sufficient to enable us to fix such limits with precision. Nevertheless, from such charts of the currents of the Atlantic as Schott's[12] and Meyer's[13] we may arrive at some approximately accurate estimate of the lateral extent of the Gulf Stream.

It has generally been taken that the inner edge of the Gulf Stream, from its outfall into the sea to Cape Hatteras, is defined by the 100-fathom curve. But recent observations by the Coast and Geodetic Survey indicate that it lies closer inshore. Systematic current observations made on board Diamond Shoals Light Vessel, which is anchored in 30 fathoms of water off the coast of North Carolina about 14 miles southeast of Cape Hatteras, give an average surface current here of 0.4 knot setting N. 58° E., which proves that along this stretch of the coast the inner edge of the Gulf Stream lies nearer the 20-fathom curve than the 100-fathom curve. Taking the inner limit of the Gulf Stream as far as Cape Hatteras to be defined by the 50-fathom curve, and the outer edge to be defined by a line along which the current is still approximately parallel to the axis of the Gulf Stream, the width of the stream northward of its outfall is as follows: off Cape Canaveral, about 70 miles; off the coast of Georgia after its union with the Antilles Current, about 150 miles; off Cape Hatteras about 200 miles.

Conflict with the Labrador Current

The region off Cape Hatteras has been called the "delta" of the Gulf Stream, for here the widespreading current separates into a number of bands. This is most clearly evidenced by the juxtaposition of warm and cold bands of water of varying widths. This feature is also noted below Cape Hatteras but not in so marked a degree.

North of Cape Hatteras the Gulf Stream flows with a velocity averaging a little less than a knot, turning more and more eastward under the combined effects of the deflecting force of the earth's rotation and the eastwardly trending coast line, until the region of the Grand Bank of Newfoundland is reached. Here it comes into conflict with the southorly flowing Labrador Current which carries cold water of relatively low salinity.

The Cold Wall

At an early stage of the investigations it was found that on its western or inner side the Gulf Stream was separated from the coastal waters by a zone of rapidly falling temperature, to which the term "cold wall" was applied. It is most clearly marked north of Cape Hatteras but extends, more or less well defined, from the straits to the Banks of Newfoundland. The abrupt change in the temperature of the waters separated by the cold wall is frequently very striking. Ward refers to an occasion in 1922 when the U. S. Coast Guard cutter Tampa, which is about 240 feet long, was placed directly across the cold wall, and the temperature of the sea at the bow was found to be 34° while at the stern it was 56°.[14]

In the vicinity of the Banks of Newfoundland the cold wall represents the dividing line between the warm waters of the Gulf Stream and the cold waters of the Labrador Current; and it seemed reasonable to invoke the cold waters of this current in explaining the existence of the cold wall and the relatively low temperatures of the coastal waters to the southward and westward. It was largely on this account that the waters of the Labrador Current were assumed to flow all along the eastern coast of the United States.

Recent observations, however, do not bear out this explanation. Current observation on various light vessels along the Atlantic coast of the United States made in recent years by the Coast and Geodetic Survey give no evidence of a predominant southerly movement of the water along the coast. From the observations made by the International Ice Patrol, Smith concludes that there is no southwest flow of the Labrador Current across the Great Bank, but that it "turns sharply, between parallels 42 and 43 and meridians 51 and 52, to flow easterly, parallel with the Gulf Stream." [15] In his study of the Gulf of Maine, Bigelow gave careful consideration to this question. His conclusion is that he has "no hesitation, therefore, in definitely asserting that the Labrador Current does not reach, much less skirt, the coast of North America, from Nova Scotia southward, as a regular event." [16]

Several agencies appear to be responsible for the cooler coastal waters along the eastern coast of the United States. In the first place into this area the rivers bring their drainage waters from the

land, those waters being for the greater part of the year much colder than the open ocean waters. Another contributory cause is the deflection by the earth's rotation of cold water form the Gulf of St. Lawrence against the American coast. Then, too, the coastal waters are closer to the low winter temperatures of the land and are thus made colder than the open ocean waters. A further cause is found in the winds, which along the coast of the United States are prevailingly from the land. This tends to drive the warmer surface water seaward, its place being taken by the cooler subsurface waters.

The North Atlantic Drift

When we come to a study of the horizontal circulation of the North Atlantic Ocean we find a complex system of interrelated currents, as is evident from a glance at Figure 6. In this figure,
9 which is adapted from Schott, three characteristics of the currents are indicated. The direction of the current at any point is shown by the direction of the arrow at that point; the strength of the current or its velocity is indicated by the width of the arrow; and the stability of the current is indicated by the length of the arrow. The stability of the current at any point is expressed as a percentage and is a measure of the constancy of direction of the current at that point. The derivation of the numerical value of the stability involves technical details[17] which need not detain us here.

In a very real sense the circulation indicated by Figure 5 constitutes a single-current system; for a movement of the water at any point implies corresponding movements and return currents at other

points, all these movements together forming a system of circulation. However, the large area covered by the North Atlantic Ocean and more particularly the different characteristics of the moving masses of water as regards temperature, salinity, and velocity make it convenient to designate various parts of the system by distinctive names, as for example the North Equatorial Current or Canary Current.

Starting at any given point various circuits may be traced on a current chart. The one which, under the name of Gulf Stream, we have followed from the Straits of Florida as far as the Banks of Newfoundland may be traced further eastward and northeastward to the coastal waters of northwestern Europe, as shown in Figure 6. Shall this current circuit from the eastern coast of the United States to northwestern Europe be designated by the single name Gulf Stream? Or shall we limit the name Gulf Stream to the stretch from the Straits to the Banks of Newfoundland, since in this stretch the characteristics of the current are much the same? If it is the northeasterly transport of warm water across the Atlantic that one has in mind, a single name like Gulf Stream or North Atlantic Current has many advantages. If, however, the causes and details of the movement of the water are being studied, the phenomena are more clearly apprehended by giving the current eastward of the Banks of Newfoundland some such name as Gulf Stream Drift or North Atlantic Drift. It is a slow current, the velocity averaging less than half a knot, and its movement is due in large part to the westerly winds which prevail over this stretch of the ocean.

The validity of the conception underlying the representation of the movement of the waters in the Gulf Stream and in the North Atlantic Drift by current charts like Figure 7 has been assailed in recent years by Dr. E. Le Danois. In a paper published in 1924[18] he elaborates the thesis that the movement of the waters of the North Atlantic consists of two currents—a circumpolar current and an equatorial current—and various so-called transgressions, by which name he denominates slow periodic movements of the water of the nature of long-period tidal movements. The Gulf Stream in particular he reduces to a mixture of the equatorial current with the tidal current from the Gulf of Mexico, which tidal current he mentions as being violent. "This tidal current—the true Gulf Stream— is compelled to move into the open sea by the presence of the last waters of the Labrador Current which skirt the coast of the United States." (p. 19).

Now there are data at hand, as we shall see later, which completely disprove the existence of violent tidal currents in the Gulf of Mexico. Moreover, in characterising the current in the Straits of Florida as a tidal current Le Danois must have in mind something quite different from what is commonly understood by the term, namely, a periodic forward and backward movement of the water with a period of half a day or a day. And in invoking the presence of the Labrador Current along the coast of the United States he surely does not strengthen his case; for, as we have seen, the view that the Labrador Current reaches the coast of the United States is no longer tenable.

The reality of the movement of the water from the lower latitudes of the western North Atlantic to the higher latitudes of the eastern North Atlantic is not only evidenced by a chart of the currents but is also clearly indicated by the temperature of the surface waters. In Figure 7 the isotherms of the surface waters of the North Atlantic are shown for each five degrees Fahrenheit. The northerly sweep of the isotherms in the eastern North Atlantic points clearly to the existence of a current moving easterly and northerly across this oceanic basin.

Causes of the Gulf Stream

Ocean currents may arise from any one or more of a number of causes. Some of these causes reside within the sea itself, others originate without. Differences in level between two regions of an ocean basin, brought about by whatever agencies, will result in a surface current from the higher to the lower level. Differences in density, whether arising from difference in temperature or in salinity or both, will bring about a subsurface current from and a return surface current to the region of greater density. Differences in atmospheric pressure between two regions will, in the same way, bring in their train a subsurface current from and a return surface current to the region of greater pressure. And in the wind we have at once the most obvious and the most familiar of the agencies that bring about ocean currents.

In a current traversing so long a course as that of the Gulf Stream it is plain that all the agencies enumerated above enter as factors. Clearly, too, the relative importance of the different agencies must vary in different parts of the course. But various problems of an hydrodynamic character must yet be solved before a numerical evaluation of the relative importance of the agencies concerned in the movement of the Gulf Stream is possible.

A century and a half ago Franklin thought that the Gulf Stream "is probably generated by the great accumulation of water on the eastern coast of America between the tropics, by the trade winds which constantly blow there." And in the trade winds, which bring about a westerly flow of the waters in the equatorial regions of the Atlantic Ocean, is still found the primary cause of the Gulf Stream. As appears from Figure 6, the waters of the South Equatorial Current are the first to strike the coast, the greater part being directed northwestward into the Caribbean Sea where they reinforce the flow of the North Equatorial Current. From the Caribbean the combined flow comes into the Gulf of Mexico whence it issues as the Gulf Stream into the Straits of Florida.

Now while the Gulf Stream is traced to the trade winds, the stream is not a wind or drift current as are the North and South Equatorial Currents. The accumulation of water resulting from the trade winds brings about a gradient current. This means that a
302 higher level of /the water must obtain in the Gulf of Mexico than out in the open sea north of the Straits of Florida. Agassiz quotes Hilgard as regarding the Gulf of Mexico "as an immense hydrostatic reservoir rising to the height of more than 3 feet

above the general oceanic level, and from this supply comes the Gulf Stream, which passes out through the Straits * * * the only opening left for its exit."[19] And in a footnote he adds, "By a most careful series of levels, run from Sandy Hook and the mouth of the Mississippi River to St. Louis, it was discovered that the Atlantic Ocean at the first point is 40 inches lower than the Gulf of Mexico at the mouth of the Mississippi." In a paper published in 1914 Hepworth states, "As regards the Gulf Stream, and its causation, it was found by the officers of the United States Coast Survey that the Atlantic Ocean at Sandy Hook was 3 to 4 feet lower than the waters of the Gulf of Mexico at the mouth of the Mississippi."[20]

It should be remembered that leveling of even the highest precision is subject to instrumental errors which, while very small for moderate distances, may become relatively large between widely separated points. More recent results reduce very much the difference in level between the Gulf of Mexico and the Atlantic and bring to light the fact that this is a highly involved matter. Avers recently studied this question in connection with the broader question of the deviations of local sea level from a level surface.[21] His results, which are based on the best available data, may be summarized as follows: From Galveston, Texas, to Cedar Keys, on the west coast of Florida, the level of the Gulf slopes downward, the difference between the two places being 0.43 foot. The level of the Gulf at Cedar Keys is 0.36 foot higher than the level of the Atlantic Ocean at St. Augustine on the eastern coast of Florida. But from St.

Augustine northward there is an upward slope of sea level all along the Atlantic coast of the United States; so that in the vicinity of Sandy Hook sea level is actually 0.62 foot higher than at St. Augustine and but 0.16 foot below the Gulf level at Galveston.

This upward slope of sea level along the Atlantic coast of the United States does not necessarily mean that the Gulf Stream is moving uphill. For the main body of the Gulf Stream is a number of miles off the coast, and there may well be a downward slope of sea level outward from the coast. The question of sea level itself is one complicated by many factors, and the exact determination of the difference in level between the Gulf and the open sea bristles with numerous unsolved problems.

Fluctuations of the Gulf Stream

03 The Gulf Stream manifestly must be subject to fluctuations as regards location, velocity, and temperature. Heavy winds will not only carry its waters into regions which at other times it does not invade but will also accelerate or retard its velocity. Variations in barometric pressure likewise will bring about fluctuations in the movement of the waters of the stream. Seasonal variations in temperature in the regions through which it flows will be reflected in somewhat similar seasonal variations in the temperature of its waters. A further cause for its fluctuation is found in the fluctuations of the currents which feed it or which, like the Labrador Current, come into conflict with it.

Fluctuations in the velocity of the Gulf Stream are noted by Pillsbury. He refers to an occasion, while he was at anchor in the Straits of Florida, when the velocity of the current at the surface increased from 3.3 knots to 4.6 knots in less than an hour. He speaks, too, of "a regular daily variation in velocity which amounts in some instances to nearly 2½ knots" (p. 546). This regular daily variation he regarded as of the nature of a tidal effect. His observations were later subjected to harmonic analysis by Harris, who found the principal constituent of the tidal current to have a velocity of less than a quarter of a knot.[22] The tidal current in the Straits of Florida is therefore of negligible velocity, and the fluctuations noted by Pillsbury are undoubtedly irregularities which accompany the flow of water in large masses.

Pillsbury was also of the opinion that, in addition to this so-called regular daily variation and to fluctuations arising from changes in wind and weather, the Gulf Stream within the Straits of Florida was subject to periodic monthly variations in both temperature and velocity which depend on the declination of the moon. The observations are not, however, sufficiently extensive to settle this question definitely. The reality of such variations is still in question, and it would not be at all surprising if further investigation should disprove any such relationship.

In a paper before the American Meteorological Society on Temperature Variations in the Gulf Stream in the Straits of Florida, 1917-1921,[23] Hazel V. Miller presented the results of a study of several thousand readings of surface-water temperature made by observers on the Key West-Habana car ferries across the Straits of Florida for the 4-year period 1917-1921. The temperature was found
304 to range from a minimum of about 76° in January to about 86° in September, while variations of as much as 4° from week to week under the influence of a strong wind were noted. A comparison of weekly temperatures with winds brought out clearly immediate and persisting effects of the wind as regards both direction and velocity.

From the nature of the agencies concerned, fluctuations from day to day in the flow and temperature of the Gulf Stream may be taken for granted. Seasonal variations likewise are unquestionable, as are smaller fluctuations from year to year. Vilhelm Pettersson studied the temperature data derived from ships' logs, covering the Gulf Stream up to latitude 33° N., for the 14-year period 1900-1913. He found that the temperature of the surface waters varies from year

to year, generally by less than 1° but sometimes by more than a degree.[24] Whether these yearly variations are, in large or small part, of a periodic nature is at the present time, for lack of sufficient data, an open question.

The difficulties involved in securing systematic observations on the temperature and flow of the Gulf Stream to determine the nature and extent of its fluctuations are obvious. The observations recorded in navigators' log books furnish valuable information, but such observations are not sufficient of themselves. More hopeful is the slowly growing use of sea-water thermographs aboard ships. From the records furnished by these instruments definite information regarding fluctuations in the temperature of the Gulf Stream waters should result.

In the light of the preceding considerations the question of whether there has been any permanent change in the course or in the temperature of the Gulf Stream since it has been known to civilized man, may be answered shortly. Manifestly, without extensive observations which would permit comparisons, no categorical answer can be given. But it is clear that any decided change in an ocean current of the magnitude of the Gulf Stream can come only as the result of extensive changes in such features as the bottom of the ocean, the configuration of the coast line, or the prevailing winds. Since no such extensive changes appear to have taken place, it is highly improbable that any decided change in the course of the Gulf Stream has occurred since it has become known.

Climatic Effects

A host of problems lie covered by the question of the climatic effects of the Gulf Stream. That its warm waters have an ameliorating effect on the lands near which they flow is a strongly held opinion; and now and again schemes are seriously proposed to change the course of the Stream with a view to moderating the winter climate of our Northeastern States.

A moment's consideration is sufficient to show that the direct influence of the Gulf Stream on the climate of the greater part of the eastern coast of the United States is altogether negligible. For, aside from latitude, our climate depends mostly on the direction from which the winds come and the force with which they blow. In winter the winds along the northeastern coast of the United States are prevailingly from the northwest, that is from the land. Hence the warm waters of the Gulf Stream lying several hundred miles to the leeward can in no way moderate our winter climate.

These considerations are sufficient also to prove the absurdity of the proposals for changing the course of the Gulf Stream in the interests of a more equable climate. Furthermore, the forces that give rise to the Gulf Stream are of such magnitude that they are not yet amenable to control by man. But even if the Gulf Stream could be brought nearer our shores, the climate could be moderated only if the winter winds could be made to blow from the south or the southeast.

Indeed, there are good reasons for believing that if the Gulf Stream were to shift closer to the coast the climate of our Northeastern States would become more extreme rather than moderated—colder and more stormy in winter, hotter and more humid in summer. For, with warm air near the coast in winter, a greater flow of air near the coast in winter, a greater flow of air from the northwest would result, bringing severer storms and colder weather. In summer, the winds along the coast are more or less sea breezes, bringing the cooler air from the sea to moderate the heat. With warmer air nearer shore, the sea breezes would become weaker and less frequent, thus giving wider scope for the hot land winds.

While the moderating effect of the Gulf Stream on the climate of North America is negligible, there is no question as to its beneficent effects on the climate of northwestern Europe. Scandinavia and southeastern Greenland face each other across the intervening waters of the Atlantic Ocean along the same parallels of latitude. Contrast the populous and prosperous lands of the one with the bleak and inhospitable shores of the other!

It is to be observed that the tempering influence of the Gulf Stream on the climate of northwestern Europe is effected through the agency of winds. In winter the winds are there prevailingly from the southwest. Blowing over the relatively warm water which the Gulf Stream (using the term as embracing also the North Atlantic Drift) has brought to the northeastern rim of the Atlantic, they carry warm air onto the coast. It is through this

306 mechanism that the heat exchange /in winter between the Gulf Stream and the air of northwestern Europe takes place.

How great the influence of the Gulf Stream on the climate of northwestern Europe is, becomes evident from the fact that the average temperature for the month of January in northern Norway is about 45° above the January temperature normal for that latitude.[25] Hammerfest, on the north coast of Norway in latitude 70° 40' N.—well within the Arctic Circle—is an important harbor and sea-fishing center during the winter, while the port of Riga, about 800 miles farther south is obstructed by ice throughout the season.

Since the climate of northwestern Europe is so strongly influenced by the Gulf Stream, should not fluctuations in the latter find reflection in changes in the climatic conditions of this region? At first glance the differences in temperature of the Gulf Stream from year to year—something like 1°—might appear insignificant in such a connection. But the fact is not to be overlooked that the capacity of water for heat is so great that when a given volume of water gives off the heat represented by a fall of 1° in temperature, a mass of air more than 3,000 times that volume will have its temperature raised 1°.

A direct attack on this problem is difficult because of the lack of systematic observations on the temperature and flow of the Gulf Stream. Otto Pettersson studied the temperature variations of the water at several places along the Norwegian coast and found

that these variations were reflected by corresponding variations in various climatic phenomena.[26] The problem clearly is a complicated one involving the question of the mutual interaction of ocean and atmosphere. A considerable literature has grown up around this, which is summarized by Helland-Hansen and Nansen.[27]

One phase of this problem links with the question of long-range weather forecasts. It is a long circuit that is traversed by the Gulf Stream from its place of origin in the subtropical regions to the coasts of northwestern Europe. How long a period intervenes between fluctuations in the stream and the resultant climatic effects in Europe? This problem, too, can not yet be attacked directly, because of the lack of systematic observations. Such investigations as have been made show this to be a promising field. Thus Otto Petterson found that the date when spring plowing could commence near Upsala depended on the temperature of the water of the Atlantic off the coast of Norway about two months previous. Vilhelm Petterson found that the summer temperature of the water in the region between Newfoundland and Ireland gave an indication of the rainfall in Ireland and Great Britain in the following year.

Obviously the problem of unraveling the relationship between changes in the Gulf Stream and weather conditions several months hence is not a simple one. Climatic conditions in any given region of the North Atlantic result from the interplay of a number of factors. Similarly, the temperature of the stream at any given time

is brought about by the interaction of a number of agencies. Neverthe-less it appears that in the study of the fluctuations of the Gulf Stream lies the possibility of long-range weather forecasts for a considerable part of Europe.

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